

Evidence for charmonium generation at the phase boundary in ultra-relativistic nuclear collisions

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Abstract

We investigate the transition from suppression to enhancement of J/ψ mesons produced in ultra-relativistic nuclear collisions in the framework of the statistical hadronization model. The calculations are confronted with the most recent data from the RHIC accelerator. This comparison yields first direct evidence for generation of J/ψ mesons at the phase boundary. Based on the success of this approach we make specific predictions for LHC energy.

Twenty years ago the J/ψ meson was proposed [1] as a crucial observable for the diagnosis of the Quark-Gluon Plasma (QGP) produced in ultra-relativistic nucleus-nucleus collisions. Since then this probe has been the focus of intense experimental and theoretical efforts. In the course of these, it was recently realized [2] that even complete J/ψ melting in the QGP via Debye screening [1] could lead to large J/ψ yields due to production at the phase boundary (hadronization). Predictions using the corresponding statistical hadronization model (SHM) [2,3] met with initial success when compared to data. In a different approach, based on the kinetic model [4], the J/ψ production is described via dynamical melting and (re)generation over the whole temporal evolution of the QGP [5,6,7]. Transport model calculations [8,9] were also performed. We note that, in general, the generation can only take place effectively if the charm quarks reach thermal (not chemical) equilibrium and are free to travel over a large distance, corresponding to about one unit in rapidity, implying deconfinement. Inherent to both statistical and kinetic approaches is that the charmonium production scales quadratically with the number of charm quark pairs.

In the following we base our investigations on the detailed approach for charmonium production developed recently [10] in the statistical hadronization model. In this study we have explored the dependence of model predictions on various input parameters and shown that the experimentally observed J/ψ phase space distributions can be well reproduced.

We focus in this note on the rapidity and centrality dependence of the nuclear modification factor

$$R_{AA}^{J/\psi} = \frac{dN_{J/\psi}^{AA}/dy}{N_{coll} \cdot dN_{J/\psi}^{pp}/dy} \quad (1)$$

which relates the yield in nucleus-nucleus collisions to the yield expected from a superposition of independent nucleon-nucleon collisions. Here, $dN_{J/\psi}/dy$ is the rapidity density of the J/ψ yield integrated over transverse momentum and N_{coll} is the number of binary collisions for a given centrality class. Recently, a comprehensive set of data on J/ψ production in Au-Au [11] and pp [12] collisions at $\sqrt{s_{NN}}=200$ GeV has been released by the PHENIX collaboration.

In the following we employ for the calculations of J/ψ yields in nucleus-nucleus collisions the charm production cross section calculated in perturbative QCD (pQCD) for RHIC [13,14] and LHC [15] energies¹. In the absence of accurate pQCD calculations for the J/ψ production cross section in pp collisions we use the PHENIX data [12] at RHIC energy, while for the LHC energy we extrapolate the Tevatron cross section [18] (see discussion in ref. [10]).

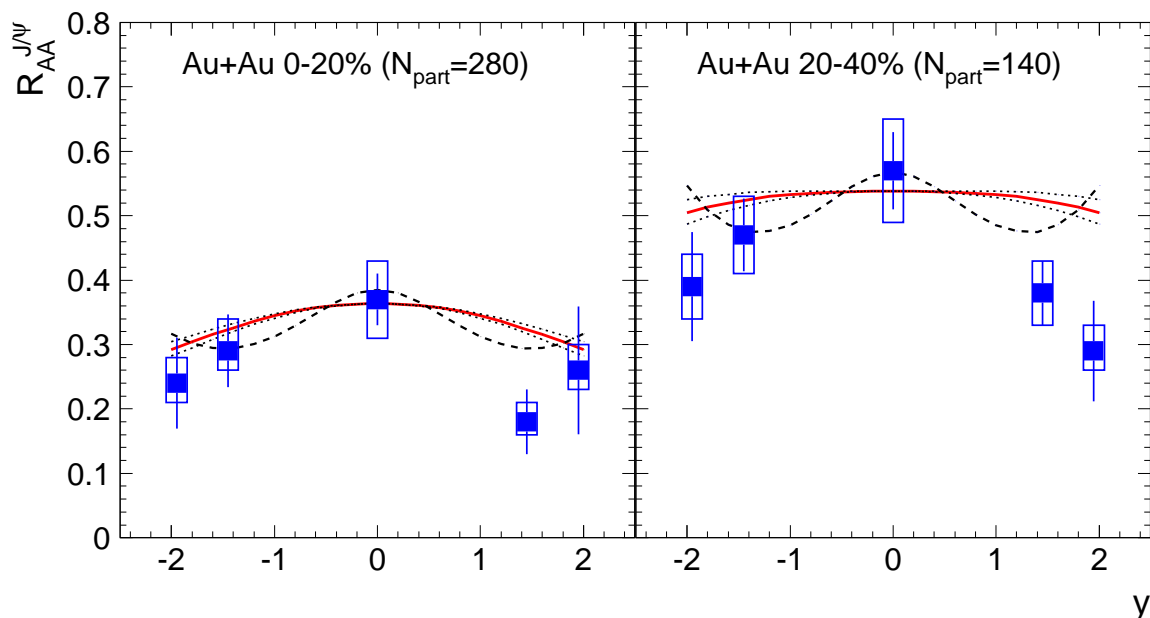


Fig. 1. Rapidity dependence of $R_{AA}^{J/\psi}$ for two centrality classes. The data from the PHENIX experiment (symbols with errors) are compared to calculations (lines, see text). For the data [11], the error bars show the statistical and uncorrelated systematic errors added in quadrature, while the correlated systematic errors are represented by the boxes. Note that a global systematic error of the order of 10% has to be additionally applied [11].

¹ A larger charm production cross section, as inferred indirectly and with large uncertainties by the PHENIX [16] and STAR [17] experiments, will, if substantiated, degrade the level of agreement between model calculations and data.

In Fig. 1 we present the rapidity dependence of $R_{AA}^{J/\psi}$. For the model calculations we have considered two scenarios for the J/ψ data in pp collisions [12]. We have fitted the measurements with a gaussian², with a resulting width in rapidity $\sigma_y = 1.63 \pm 0.05$. This case is shown with continuous lines in Fig. 1, with the error of σ_y denoted by the dotted lines. A fit with 2 gaussians, which describes the pp data somewhat better statistically [12] but is rather unmotivated theoretically, leads to the results shown as the dashed lines in Fig. 1. The resulting structure in $R_{AA}^{J/\psi}$ is caused exclusively by this description of the pp data. In both cases, our calculations reproduce rather well (considering the systematic errors) the $R_{AA}^{J/\psi}$ data. The sensitivity of the results on the assumed shape of the rapidity distribution in pp collisions strongly underlines the necessity of better quality data.

Our model describes the observed larger suppression away from midrapidity. We note that this trend is opposite to that expected from the melting model [1,19], where $R_{AA}^{J/\psi}$ is constant or exhibits a minimum at midrapidity. The maximum of $R_{AA}^{J/\psi}$ at midrapidity is in our model due to the enhanced generation of charmonium around mid-rapidity, determined by the rapidity dependence of the charm production cross section. In this sense, the above result constitutes the first unambiguous evidence for the statistical generation of J/ψ at chemical freeze-out. In detail, our model is in better agreement with the data for the central bin (0-20%), while the prediction for the mid-central (20-40%) centrality class exhibits a somewhat flatter shape than observed in the data. Shadowing effects in nucleus-nucleus collisions at RHIC energy are rather small and not firmly established [15]; we have hence neglected them. Inclusion of shadowing corrections would somewhat reduce $R_{AA}^{J/\psi}$ at forward and backward rapidities and might further improve the quantitative description of the J/ψ data. At LHC energy, since the expected shape in rapidity of the charm production cross section is much flatter compared to that at RHIC energy [14,15], we expect less pronounced features for the rapidity dependence of charmonium production [10].

The centrality dependence of $R_{AA}^{J/\psi}$ at midrapidity is shown in Fig. 2. Our calculations approach the value in pp collisions around $N_{part}=50$, which corresponds to an assumed minimal volume for the creation of QGP of 400 fm^3 [10]. The model reproduces very well the decreasing trend versus centrality seen in the RHIC data [11]. We have not included in our calculations the smearing in N_{part} due to finite resolution in the experimental centrality selection. This effect would lead to a better agreement with data for peripheral collisions. Note that in our model the centrality dependence of the nuclear modification factor arises entirely as a consequence of the still rather moderate rapidity density of initially produced charm quark pairs ($dN_{c\bar{c}}/dy=1.6$). In contradistinction, at the much higher LHC energy, $\sqrt{s_{NN}}=5.5 \text{ TeV}$, the charm production cross section is expected to be about an order of magnitude larger [15,10]. In this case, the canonical suppression is sizable only for peripheral collisions (the canonical correction is less than 10% for $N_{part} > 100$, see Fig. 1 in ref. [10]). As a result, a totally opposite trend as a function of centrality is predicted, see Fig. 2, with $R_{AA}^{J/\psi}$ exceeding unity for central collisions. A significantly larger enhancement of about a factor of 2 is obtained if the charm production cross section is two times larger than presently assumed.

² We note that the fitted gaussian is very close to the shape of the rapidity distribution of the pQCD charm production cross section [14].

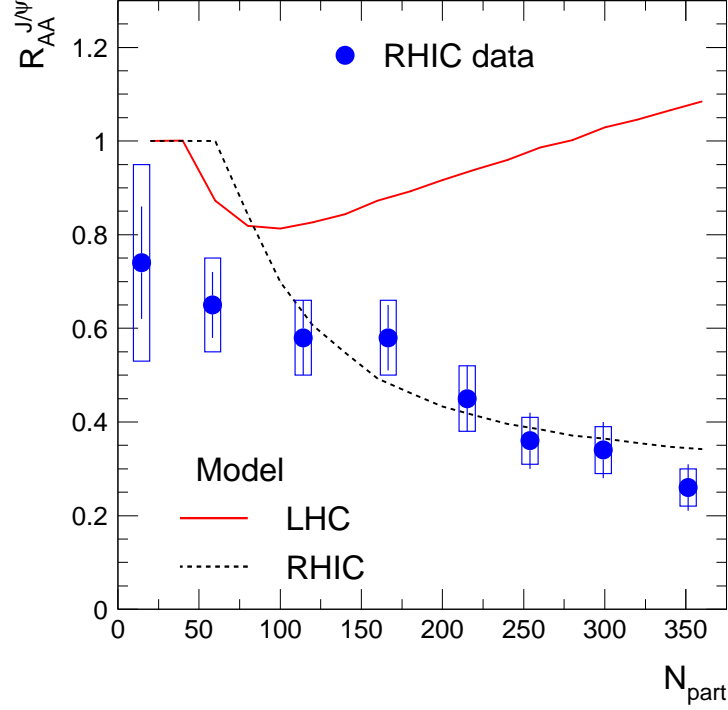


Fig. 2. Centrality dependence of the relative J/ψ yield $R_{AA}^{J/\psi}$ at midrapidity.

In summary, by analyzing the rapidity dependence of the nuclear modification factor for J/ψ production recently published by the PHENIX collaboration we have identified, for the first time, a clear signal for generation of charmonia due to statistical hadronization at the phase boundary. Our calculations describe well the measured decrease with centrality and the rapidity dependence of $R_{AA}^{J/\psi}$ at RHIC energy. Extrapolation to LHC energy leads, contrary to the observations at RHIC, to a J/ψ nuclear modification factor increasing with collision centrality and exceeding unity for central collisions. While the exact amount of enhancement will depend on the precise energy dependence of the charm production cross section, the trend is a robust prediction of the model. If the predicted centrality dependence is observed, this would be a striking fingerprint of deconfined and thermalized heavy quarks in the QGP.

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